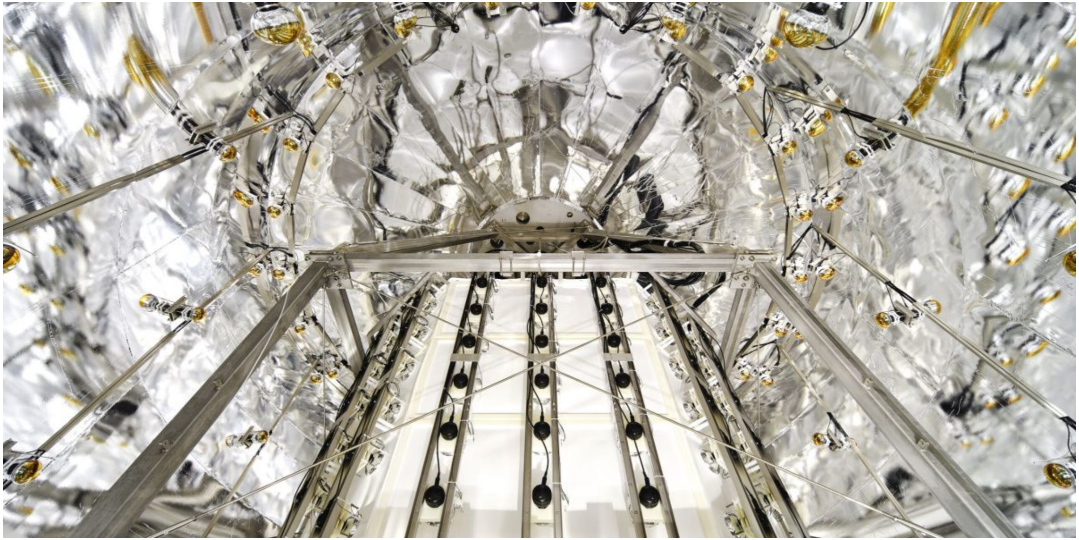
Cosmology, Astro- and Astroparticle Physics



XENONnT inside the watertank (https://xenonexperiment.org/photos/)

Astrophysics and General Relativity

Prof. Philippe Jetzer

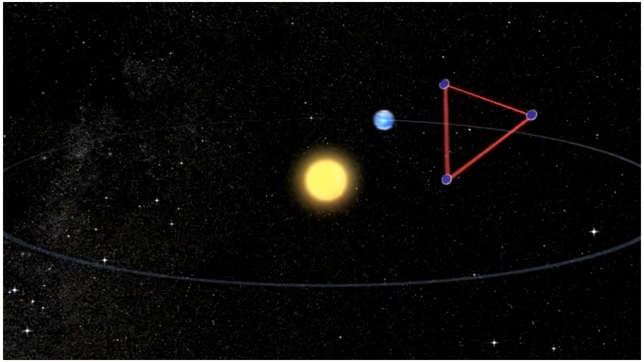
LIGO (Laser Interferometer Gravitational-Wave Observatory) consists of two Earth-bounded instruments together with Virgo aimed to detect gravitational waves in the frequency range from about 10 to 1000 Hz. In 2015 the first gravitational wave signal has been detected. Since then more than 100 events have been found. Our group has made important contributions to the analysis of LIGO/Virgo data and in the modelling of more accurate gravitational waveforms. The latter results are used in LIGO/Virgo data analysis and in future for the LISA mission and the Einstein Telescope project.

https://www.physik.uzh.ch/g/jetzer

The work of the group is focused on the topic of gravitational waves in the framework of the LIGO Scientific Collaboration and for the future space mission LISA, since our group is involved in both of these international collaborations. In the following we briefly describe some results published in 2023, besides all the works appeared in the framework of the LIGO/Virgo, LISA Pathfinder and LISA collaborations.

P. Jetzer as a member of the LISA Science Working Team of ESA was involved in the writing of the Definition Study Report for LISA. This report is an important contribution towards the so-called Mission Adoption of LISA, which was decided on 25 January 2024, and which marks the end of various study phases and the beginning of the construction of the satellites.

Gravitational wave detections offer insights into the astrophysical populations of black holes in the universe and their formation processes. Detections of binaries consisting of black holes lying outside the bulk distribution of the astrophysical population are particularly intriguing. In a study by Y. Xu and E. Hamilton, they investigated the detectability of precession and its potential degeneracy with eccentricity in some gravitational wave events. They found that eccentricity lower than 0.2 is insufficient to mimic precession in parameter estimation when assuming a quasicircular signal. Thus their results suggest that a certain degree of precession is nec-



LISA will consist of three spacecraft, millions of kilometres apart, following the Earth on its orbit around the sun. The spacecraft will send signals to each other and the interference patterns will enable scientists to reconstruct the gravitational waves in space. (Image: AEI, MILDE)

essary to produce evidence of high precession in parameter estimation, but it remains challenging to conclusively determine which effect is responsible for the high precession observed in events like GW190521.

E. Hamilton with L. London and M. Hannam found a simple formula for the effective ringdown frequencies of the gravitational-wave signal of a precessing black-hole binary in the coprecessing frame. This formula requires only knowledge of the quasi-normal mode frequencies of the system and the value of the precession angle β during ringdown. Such a formula will be useful in modeling precessing systems. They also provide a comprehensive description of the oscillations in the ringdown frequency in an inertial frame where the spin of the final black hole is orthogonal to the orbital plane. These oscillations arise due to the superposition of the prograde and retrograde frequencies.

Highlighted Publications:

1. Measurability of precession and eccentricity for heavy binary-black-hole mergers,
   Y. Xu, E. Hamilton, Phys. Rev. D107 (2023), 103049, arXiv:2211.09561.
2. Ringdown frequencies in black holes formed from precessing black-hole binaries,
   E. Hamilton, L. Londan, M. Hannam, Phys. Rev. D107 (2023), 104035, arXiv:2301.06558.

Theoretical Astrophysics

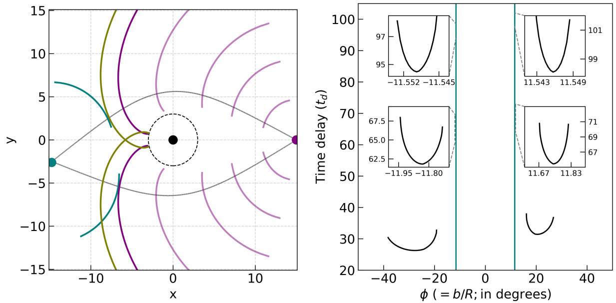
Prof. Prasenjit Saha

Our research has been on diverse astrophysical phenomena involving light and gravity, especially gravitational lenses, but also novel applications of spacecraft ranging.

https://www.physik.uzh.ch/g/saha

Galaxies and clusters that create multiple mirages of background galaxies through gravitational lensing have long been understood as a probe of dark matter and indeed the process of galaxy formation. We have continued our long-running research program in this area, and also studied less-explored regimes of lensing, such as strong gravitational fields.

In other work we have continued our study of a future Uranus mission and similar spacecraft as a detector of long-period gravitational waves, in the gap between the LISA and PTA ranges.



Wavefronts and light travel times near a black hole, similar to those arising in the famous photon-ring images around the M87 black hole.

Highlighted Publications:

1. What are the parities of photon-ring images near a black hole?
   A. Meena, P. Saha, The Open Journal of Astrophysics, vol. 6, id. 50 (2023)

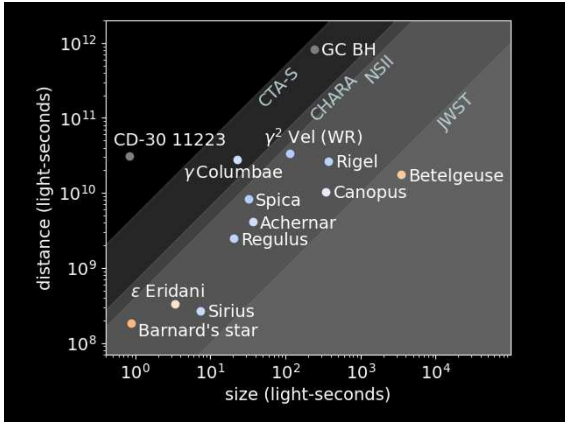

CTA – Cherenkov Telescope Array

Prof. Prasenjit Saha, Prof. Nico Serra

The Cherenkov Telescope Array (CTA) is a next-generation facility to observe high-energy sources in the Milky Way and beyond. It is designed especially for gamma-ray photons from 10 GeV to above 100 GeV, which it will detect indirectly, through optical Cherenkov showers in the atmosphere. Fortuitously, the facility will also have the capacity to operate in a completely different mode, as an optical intensity interferometer, which can image stellar-scale phenomena.

https://www.physik.uzh.ch/r/cta

We have continued our developmental simulation work on the CTA, as well as contributing to the precursor telescopes of MAGIC in intensity interferometry mode to resolve stars below the milli-arcsecond range.

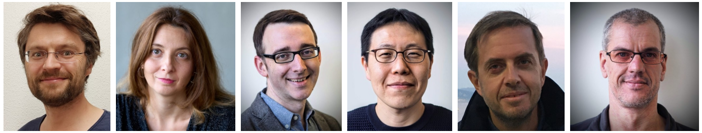


Indicative resolutions of the CTA in intensity interferometric mode, compared with other interferometric and standard telescopes.

Performance and first measurements of the MAGIC Stellar Intensity Interferometer,
MAGIC Collaboration, preprint arXiv:2402.04755

Theoretical Astrophysics

Institute for Astrophysics



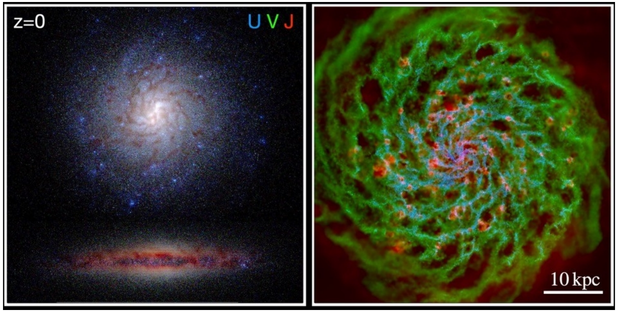
As of January 2024 the Institute für Astrophysik has been established, gathering all groups working on theoretical and computational astrophysics and cosmology that were previously part of the Institute of Computational Science (ICS).
https://www.ics.uzh.ch/

In the field of planetary science, the group of Helled continued the efforts in preparing the science case for a Uranus mission, in characterizing exoplanets, and in simulating planet formation and evolution. We also continued our involvement in space missions including Juno, JWST, Ariel and Plato. The group of Helled and Stadel together also made progress in simulating giant impacts using a new hydrodynamical method for non-ideal fluids.

Cosmological probes are affected by fluctuations of wavelength larger than the horizon scales. This infrared sensitivity in cosmological probes is canceled in general relativity (GR). Yoo's group has quantified the general conditions for such cancellation in theory of gravity beyond GR. Research interests lie within the fields of cosmology and theoretical astrophysics, working on nonlinear structure formation as well as the astrophysical aspects of different dark matter models.

Collectively, groups at the institute made progress on one of the most active frontiers in astrophysics — the study of galaxies in the young Universe. In addition to being involved in various observational projects with JWST, we made advances in the numerical modeling of the physics of galaxy formation, including feedback from stars and supermassive black holes. The new state-of-the-art FIREBOX galaxy formation simulation in a full cosmological volume, designed and performed by the Feldmann group has marked a new milestone in this field. In addition, we are developing generative machine learning methods for applications with the Square Kilometer Array Observatory (Feldmann group), and for the modeling of gravitational wave sources (Mayer group).

The groups of Feldmann, Mayer and Schneider are deeply involved in SKACH, the Swiss SKA Consortium, and contributed to obtain longterm funding from the federal government to support swiss research in SKA. To



Visualization of the multiphase structure of the interstellar medium in one of many Milky Way like galaxy in FIREbox. (Left) Color composite image showing the stellar and dust components of the depicted galaxy in a face-on and edge-on view. (Right) Face-on, color composite image of the galaxy's molecular (blue), atomic (green), and ionized (red) hydrogen content.

gether with groups at EPFL, UniGE and ETH, they also recently joined the Millimeter Wave Array (MWA), an Australian radio-telescope facility precursor of SKA. The ICS also hosted the main international swiss-based SKA meeting.

The group of Mayer, together with the team of Prof. Ciorba at UniBasel, managed to begin production mode with the first Exascale particle-based simulation code in astrophysics and cosmology, SPH-EXA, whose development has been funded over the past 6 years through the Platform for Advanced Scientific Computing and the Swiss National Supercomputing Center. Owing to SPH-EXA, in October 2023 they were awarded the "EuroHPC Extreme Access Scale Award", the largest ever supercomputing time allocation in Europe across all disciplines of science and industry. With that they are running, on the LUMI supercomputer, simulations of the turbulent interstellar medium and star formation which can resolve for the first time the full turbulent cascade down to the scale pre-stellar core formation.

Team members in Mayer's group also made progress in the field of gravitational wave astrophysics, developing a new model for the origin of the first supermassive black holes in the early Universe, the dark collapse scenario, which generates a gravitational wave burst detectable with the Laser Interferometer Space Antenna (LISA), and showing how waveforms generated by in-spiraling massive black hole binaries can be altered in a detectable way by perturbations form matter surrounding the black holes.

1. Conditions for the absence of infrared sensitivity ...
   M. Magi, J. Yoo, Physics Letters B **864** 138204
2. Priorities in gravitational waveforms for future ..
   L. Zwick, P. R. Capelo, L. Mayer, MNRAS **521**, 4645
3. FIREbox: simulating galaxies at high dynamic range ...
   R. Feldmann et al, MNRAS **522**, 3831
4. Towards a new era in giant exoplanet characterisation,
   S. Müller, R. Helled, A& A **669** id.A24, 11

Astroparticle Physics Experiments

Prof. Laura Baudis

We study the composition of **dark matter** in the Universe and the **fundamental nature of neutrinos**. We build and operate ultra low-background experiments to detect dark matter particles, to search for the neutrinoless double beta decay, a rare nuclear process which only occurs if neutrinos are Majorana particles.

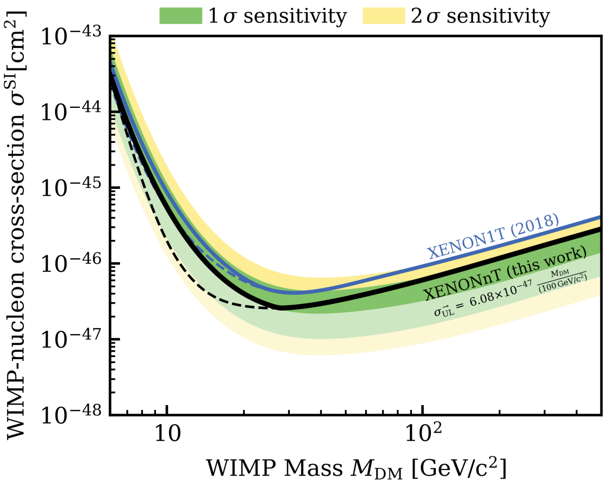
We are members of the **XENON collaboration**, which operates **xenon time projection chambers** to search for rare interactions such as from dark matter, and we lead the **DARWIN collaboration**, with the goal of building a 50 t liquid xenon observatory to address fundamental questions in astroparticle physics.

We are members of the **GERDA** and **LEGEND experiments**, which look for the **neutrinoless double beta decay of ^{76}Ge** in high-purity Ge crystals immersed in liquid argon, with an unprecedented sensitivity.

https://www.physik.uzh.ch/g/baudis

Highlight: First XENONnT Dark Matter Search with Nuclear Recoils

The XENONnT experiment was designed to detect the faint and rare interactions of hypothetical dark matter particles with ordinary matter. As a popular dark matter candidate, weakly interacting massive particles (WIMPs) are expected to scatter on nuclei. The corresponding nuclear recoil would have a low energy of only few keV and experimental results indicate that it would occur at a rate of less than one event per tonne of target material per year. XENONnT uses 5.9 tonnes of xenon in a dual-phase time projection chamber to measure these signals. The required low energy threshold is achieved by measuring scintillation signals in liquid and gaseous xenon with arrays of photomultiplier tubes. The UZH group was strongly involved in the sensor characterization and array assembly. The low background could be achieved by careful material selection, also with the Gator high-purity Germanium detector operated by the UZH group, as well as active background



Limits on the interaction cross-section of WIMPs with individual nucleons as a function of the WIMP mass as set by XENONnT in 2023 (black) and XENON1T in 2018 (blue). The dashed lines indicate the raw limits while the solid lines represent the limits constrained to the median sensitivity in order to prevent exclusion of parameter space beyond the experiment's sensitivity. The 68 % and 95 % confidence intervals of the simulated sensitivity are shown in green and yellow, respectively.

mitigation measures including a water Cherenkov neutron veto and online radon removal by cryogenic distillation. The first 95 days XENONnT science data were taken in the second half of 2021. In a blind analysis, no significant excess of nuclear recoil events attributable to WIMP dark matter was found. The collaboration thus placed a best upper limit of 2.58×10^{-47} cm^2 on the spin-independent WIMP-nucleon cross-section for a 28 GeV/c^2 WIMP at 90 % confidence level. Together with the LZ and PandaX-4T experiments, XENONnT places the most stringent constraints on WIMP interactions and significantly improves on the previously leading XENON1T results with data taken in a considerably shorter time. XENONnT continues to take data for its multi-year measurement campaign with the ultimate goal of detecting dark matter interactions.

Highlighted Publications:

1. First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment,
   XENON Collab., Phys. Rev. Lett. **131** (2023) 041003
2. Electron transport measurements in liquid xenon with Xenoscope, a large-scale DARWIN demonstrator,
   L. Baudis et al., Eur. Phys. J. C 83, 717 (2023)
3. Final Results of GERDA on the Two-Neutrino Double-β Decay Half-Life of ^{76}Ge,
   GERDA Collab., Phys. Rev. Lett. **131** (2023) 142501

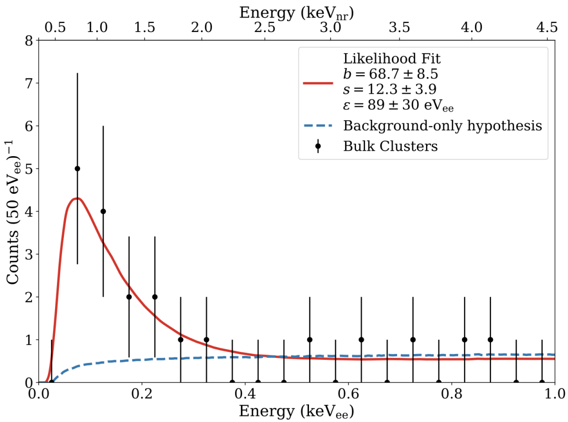
DAMIC Experiment

Prof. Ben Kilminster

DAMIC-M (Dark Matter in CCDs at Modane Underground Lab) is an experiment that searches for the dark matter gravitationally bound in our Milky Way through electrical signals produced from its collisions with silicon CCD detectors. This experiment represents a factor of 10 increase in mass, a factor of 10 decrease in the energy threshold, and a factor of 50 decrease in background rates, as compared to the current DAMIC experiment operating in SNOLAB.

https://www.physik.uzh.ch/r/damic

Our group helped found the DAMIC experiment in 2008. We are contributing readout electronics, mechanical components, and detector control and safety systems for the next phase, DAMIC-M. In 2023, DAMIC@SNOLAB took new data with improved skipper CCD readout, and confirmed a previously observed low-energy excess, now finding an excess with a significance of 5.4 Sigma. In order to understand the origin of the excess, the UZH group is pioneering a new technique to distinguish between dark matter particles causing nuclear recoils and those causing electronic recoils. We describe the characterization of the new scientific-grade CCDs in a new paper, and also describe a recent measurement with them, characterizing for the first time the Compton scattering process on valence electrons with energy levels below 100 eV. DAMIC-M has been operating a prototype detector, while the complete detector is being constructed. With this prototype, we produced a new search for the daily modulation of dark matter, and excluded previously unexplored regions of the allowed parameter space for low-mass, dark matter, which interacts electromagnetically with the detector.



Data from DAMIC@SNOLAB (black points) show an excess above the background prediction (dashed blue line) that is consistent with a signal (solid red line) with a significance of 5.4 Sigma. The signal model is generically shown as a decaying exponential, taking into account the detector efficiency.

Highlighted Publications:

1. Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs, DAMIC, DAMIC-M, SENSEI collab., arXiv2306.01717, accepted by Phys. Rev. D.
2. Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M, DAMIC-M collaboration, arXiv2307.07251, Phys.Rev.Lett. **132** (2024) 10, 101006.
3. First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons, DAMIC-M collaboration, arXiv2302.02372, Phys.Rev.Lett. **130** (2023) 17, 171003.
4. Nuclear Recoil Identification in a Scientific Charge-Coupled Device, K.J.McGuire, A.Chavarria, N.Castello-Mor, S. Lee, B. Kilminster, et al., arXiv2309.07869, submitted to Phys.Rev.D.